Differences between NSA 94-106 and IEEE 299 LF magnetic shielding measurements

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Abstract: **For the characterisation of the LF magnetic shielding of conductive materials two setups are available. Although for both methods, loop antennas are used, two different configurations are defined. The one referenced in NSA 94-106 (formerly NSA 65-6) is called the parallel setup. The one referenced in IEEE 299 (formerly MIL STD 285) is called the coplanar setup. When performing measurements under similar conditions, different values for the resulting shielding effectiveness (SE) are obtained. This paper will discuss the background why differences are occurring.**

Keywords: LF magnetic shielding, NSA 94-206, IEEE 299

I. INTRODUCTION

For the characterization of the LF magnetic shielding on conductive materials two setups are available. Both are based on the use of loop antennas, but the physical setup is different.

One is referenced in NSA 94-106 (formerly NSA 65-6) [1] and is known as the parallel setup, where both transmitting and receiving antennas are in parallel planes, and parallel with the plane of the sample under test. This is sketched in figure1.

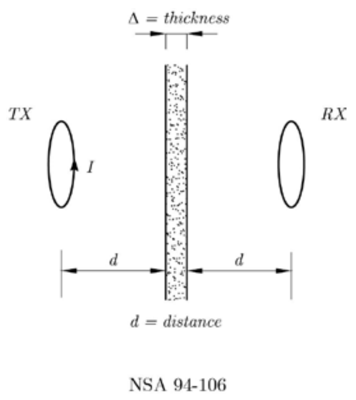

Figure 1. Basic setup for NSA 94-106 LF magnetic SE measurement

The other one is referenced in IEEE Std 299 (formerly also MIL STD 285) [2] and is known as the coplanar setup, where both antennas are located in the same plane, but perpendicular to the sample. This is sketched in figure 2.

When performing SE measurements using both methodologies, but identical samples and equipment, different results are obtained for the resulting SE values.

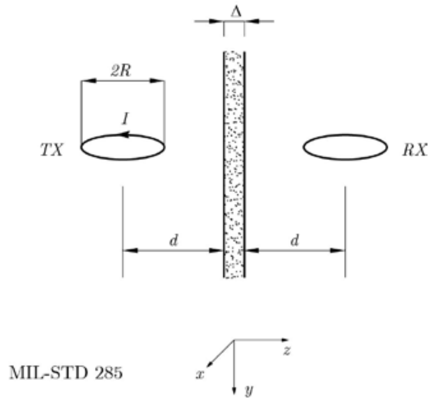

Figure 2. Basic setup for IEEE Std 299 LF magnetic SE measurement

Measurements are performed using a metal cage with an open window in one wall. The measurement setup is sketched in figure 3. A more detailed view of the fixture in order to clamp the samples is shown in the figures 4.

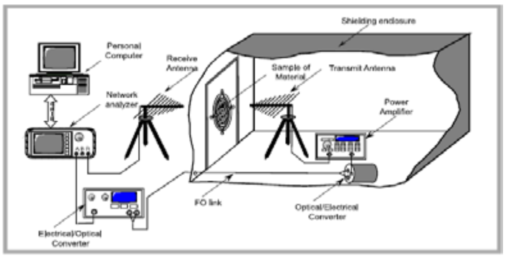

Figure 3. Global sketch of the measuring setup

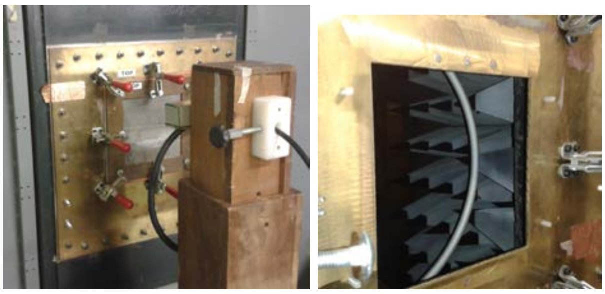

Figure 4. Pictures of the measuring setup

II. SOME THEORETICAL BACKGROUND

Theoretical analysis has been done in the past by different authors, as Bannister [9]-[10], Dahlberg and others. This resulted in some general integral formulations of the SE values, and also in some closed form approximations under certain conditions.

Recently, Celozzi [3] made an interesting analysis of both setups and the most important results of this work are summarized in the next paragraphs.

2.1. NSA 94-106 setup

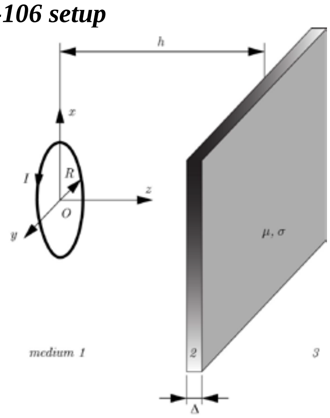

Figure 5. NSA 94-106 parallel setup

The exact solution for the SE, accounting for the physical dimensions of the transmitting loop antenna and considering as observation point the symmetrical one beyond the shield, is given by formula (1) [3]. For both antennas, the centre point is considered as reference and the distance between both is r.

$$SE = \frac{1}{4\mu_r} \frac{\int_0^\infty \frac{\lambda^2}{\tau_0} J_1(\lambda R) J_0(\lambda r) e^{-\tau_0 z} d\lambda}{\int_0^\infty K \frac{\lambda^2 \tau}{\tau_0^2} J_1(\lambda R) J_0(\lambda r) e^{-\tau_0 z - (\tau - \tau_0)\Delta} d\lambda}$$

$$K = \left[\left(\frac{\tau}{\tau_0} + \mu_r\right)^2 - \left(\frac{\tau}{\tau_0} - \mu_r\right)^2 e^{-2\tau\Delta}\right]^{-1}$$

$$\tau_0 = \sqrt{\lambda^2 - k_0^2}$$

$$\tau = \sqrt{\lambda^2 - \gamma^2}$$

$$k_0 = \omega / c_0$$

$$\gamma \cong \sqrt{j\omega\mu_0\mu_r\sigma} \tag{1}$$

Important in this configuration is the dependency of the resulting SE from only the total distance r between both antennas, the radius R of the transmitting antenna and the thickness Δ of the sample.

When translating this configuration into a Transmission Line (TL) equivalent, it requires to consider the following correct wave impedance, related to a small dipole source parallel to an conductive plane [5].

$$\eta_w = \eta_0 \frac{\left(\frac{j\omega z}{c}\right)^2 + \left(\frac{j\omega z}{c}\right)}{\left(\frac{j\omega z}{c}\right)^2 + 3\left(\frac{j\omega z}{c}\right) + 3} \tag{2}$$

where z is the distance from the observation point and c the speed of light in free space. In order to apply the TL equivalent, z = h at the position of the shield plane.

Although both the tangential electric and magnetic field components tend to vanish as the observation point tend to the loop axis, their ratio i.e. the wave impedance, is constant. Its LF approximation is valid when

$$\frac{\omega z}{c} \ll 1 \tag{3}$$

which implies, considering a loop radius R and its distance from the shield as requested by IEEE Std. 299 (2R = z = 305 mm), a maximum frequency of 16 MHz. As further tests were performed up to 20 MHz, the small dipole LF approximation may readily be used:

$$\eta_w = \eta_0 \left(\frac{j\omega z}{3c}\right) = j\omega\mu_0 \frac{z}{3} \tag{4}$$

Regarding a practical measurement setup, the source will have some finite dimensions. Therefore, a correction, ensuing from the exact integral expression, may be introduced to account for these finite dimensions of the transmitting source [3], [12]:

$$\eta_w = j\omega\mu_0 \frac{(R^2 + z^2)}{3z} \tag{5}$$

This shows a very strong dependency of the wave impedance with respect to the radius R of the transmitting antenna. It means that, even when maintaining all distances from the antennas to the sample, other values for SE might be obtained when changing the radius R of the transmitting antenna.

2.2. IEEE Std 299 setup

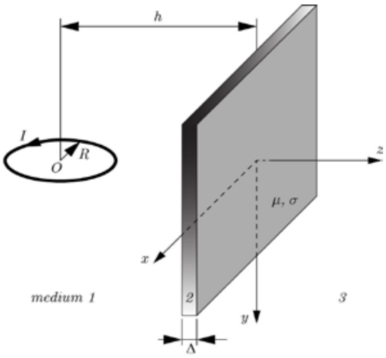

Figure 6. IEEE Std 299 coplanar setup

$$SE = \frac{\int_0^\infty \int_0^\infty \frac{\beta I_1(\beta R)}{D_1} \cos(\alpha x)\cos(\beta y) e^{-D_1|z-h|}\, d\alpha d\beta}{\int_0^\infty \int_0^\infty \frac{4\beta I_1(\beta R) D_3 e^{-(D_2-D_1)\Delta}}{D_4} \cos(\alpha x)\cos(\beta y) e^{-D_1|z-h|}\, d\alpha d\beta}$$

$$D_1 = \sqrt{\alpha^2+\beta^2}$$

$$D_2 = \sqrt{\alpha^2+\beta^2+j\omega\mu\sigma}$$

$$D_3 = D_2/\mu_r$$

$$D_4 = (D_3+D_1)^2 - (D_3-D_1)^2 e^{-2D_2\Delta} \qquad (6)$$

From the formulas (6) [3], [5]-[7], the direct dependency of the resulting SE from the distance h (from the transmitting antenna to the sample), the radius R of the transmitting antenna and the thickness Δ of the sample is observed for this configuration.

Celozzi reports also on the resulting SE by using exact formula's and different approximations for a set of materials [3], and by assuming an infinite planar shield.
In the NSA 94-106 configuration, tangential components are only generated in points away from the loop axis. The larger the region that may be taken into account, the larger is the observed effect in the field distribution, and consequently in the related SE value.
In the IEEE Std. 299 configuration, tangential components are exactly those who propagate through the shield, according to related TL simulation models. The difference of the dimensions of the transmitting loop antenna is not so relevant when the radius R is changed (under the condition of maintaining an identical current) [6] - [7].
It follows that different SE values may be obtained by using one of the two measuring setups.
Under conditions of R = 15.25 cm and the distance h from both antennas to the sample = 30.5 cm, it turns out that NSA 94-106 SE values tend to be some dB lower than the IEEE Std 299 ones.
More details can be found in appendix B of [3].

III. Measurements

Measurements have been performed on a number of different samples of materials, and 2 typical ones are summarised:

- Aluminium foil, thickness 0.1 mm
- Calandered foil, stainless steel fibers, thickness 1 mm

Measurements are performed using a metal cage of 2x2x2 m³, with an open window in one wall of 50 x 50 cm². The receiving antenna is a battery operated loop antenna EMCO 6507 and the transmitting antennas are "home made", so that they can handle up to 10 Watt transmitting power.
There is a set of three antennas with a different radii (32 cm, 20 cm and 7 cm respectively), due to the self-resonance of the antennas, and they cover the frequency range in three frequency-bands from 20 KHz - 200 KHz - 2 MHz - 20 MHz.

The resulting SE values for the NSA 94-106 setup are each time dropping when changing the transmitting antenna at the frequencies of 200 KHz and 2 MHz (blue lines in figures 7 and 8).
As it is assumed that the SE should not show a discontinuity at the same frequency, graphs are corrected with the difference between both SE values at these frequencies, in order to assume a continuous behaviour of the SE (red lines in figures 6 and 7).
So, the next graphs are showing three curves:

- NSA 94-106, as measured
- NSA 94-106 corrected for changing antenna radius R
- IEEE Std 299, as measured

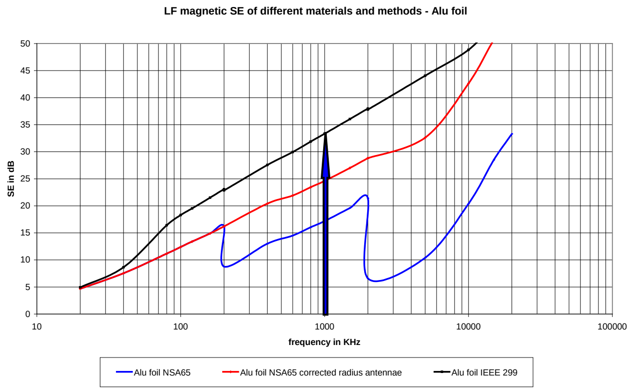

Figure 7. SE of the Aluminium foil

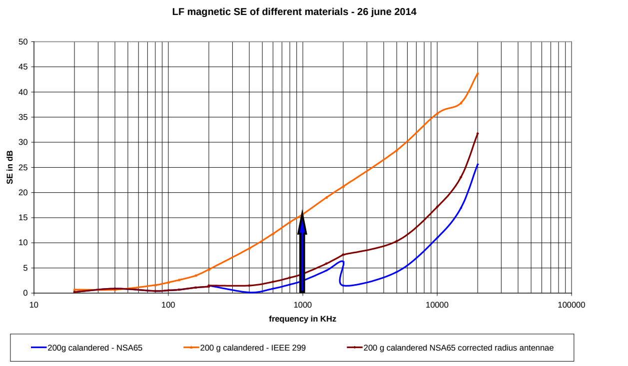

Figure 8. SE of 1 layer of 200 g calandered stainless steel foil

IV. WAVE THEORY

Schelkunoff published in 1938 a paper on the concept of using impedance in order to simulate shielding problems [4]. It is known as the wave theory applied to shielding problems of the transmission line model. As a result, the following table summarises formula's for the estimation of SE under different conditions.

Field condition	Shielding (dB) $t > \delta$ (A + R)	Shielding (dB) $t < \delta$ (R + B)
Far Field ($r > \lambda/2\pi$)	$8.69\frac{t}{\delta}+20\log\left[\frac{1}{4}\left(\frac{\sigma}{\omega\,\varepsilon_0\,\mu_r}\right)^{\frac{1}{2}}\right]$	$20\log\left[1+\frac{Z_0}{2R_s}\right]$
Near Electric dipole field ($r < \lambda/2\pi$)	$8.69\frac{t}{\delta}+20\log\left[\frac{1}{4}\frac{c}{\omega r}\left(\frac{\sigma}{\omega\,\varepsilon_0\,\mu_r}\right)^{\frac{1}{2}}\right]$	$10\log\left[1+\left(\frac{c}{\omega r}\frac{Z_0}{2R_s}\right)^2\right]$
Near magnetic dipole field ($r < \lambda/2\pi$)	$8.69\frac{t}{\delta}+20\log\left[\frac{1}{4}\frac{\omega r}{c}\left(\frac{\sigma}{\omega\,\varepsilon_0\,\mu_r}\right)^{\frac{1}{2}}\right]$	$10\log\left[1+\left(\frac{\omega r}{c}\frac{Z_0}{2R_s}\right)^2\right]$

Under the conditions of near field and a thin material, the magnetic field SE is given by the formula (token from the previous table):

$$10\log\left[1+\left(\frac{\omega\, r}{c}\,\frac{Z_0}{2\,R_s}\right)^2\right] \qquad (7)$$

with R_s the DC square resistance of the material = $1/(\sigma.t)$

The DC square resistance of both samples has been measured:

sample	DC resistance (sqohm)
Aluminium foil	0.058
Calandered SS foil	0.228

In 1969, a paper was published by A. Whitehouse [12] calculating exact wave impedances for both the parallel loop and the coplanar loop cases, and where it turned out that the LF magnetic near field approximation made by Schelkunoff is only correct for the coplanar loop or IEEE Std 299 configuration.
In case of parallel loops or the NSA 94-106 configuration, the following LF approximation can be made for the SE = R + B [11] in case of thin samples:

$$R \simeq -20\log_{10}\left|\frac{4\eta}{\eta_w+2\eta}\right|$$

$$B = 20\log_{10}\left|\frac{(\eta_w+\eta)^2-(\eta_w-\eta)^2e^{-2\gamma t}}{(\eta_w+\eta)^2}\right| \simeq 20\log_{10}\left|\frac{\eta_w 2\gamma t+4\eta}{\eta_w+2\eta}\right|$$

where $\gamma = \sqrt{j\omega\mu\sigma}$. (8)

Finally, the approximated SE is obtained as:

$$\mathrm{SE} \simeq 20\log_{10}\left|\frac{\eta_w 2\gamma t+4\eta}{4\eta}\right| = 20\log_{10}\left|1+j\omega\mu_0\frac{z}{3}\frac{\sigma t}{2}\right| \qquad (9)$$

Comparing this NSA 94-106 approximation with the Schelkunoff formula, a difference by a factor of 1/3 is observed, or a difference in SE of 10 dB may be expected in practice.
Based on the measured DC square resistances, and the thickness of the materials, the conductivity σ may be obtained. Using the above estimations of the LF magnetic field SE, as defined by Whitehouse and by Schelkunoff, the calculated SE at 1 MHz at a distance of 30 cm between source and sample is given in the next table:

sample	LF Magnetic SE in dB	
	Whitehouse	Schelkunoff
Aluminium foil	25.98 dB	35.88 dB
Calandered stainless steel foil	4.9 dB	14.5 dB

Comparing these calculated SE values with the measured ones as given in the figures 6 and 7, a good agreement is obtained with respect to both NSA 94-106 and IEEE Std 299 methods.

V. CONCLUSIONS

In this paper, the differences in LF magnetic field SE between the NSA 94-106 and the IEEE Std 299 methods has been described from the practical point of view.
Measurements show a difference in SE values, and concerning the NSA 94-106 method, the direct impact of the radius of the transmitting antenna has been demonstrated.
Resulting SE values obtained by the IEEE Std 299 are in good agreement with the theoretical wave model as defined by Schelkunoff.

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